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AN OPTICAL COINCIDENCE GAGE

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ABSTRACT

A new type of optical instrument is described which enables one to make measurements in a direction normal to the surface viewed. Furthermore, the method of operation is sufficiently simple to permit its use for routine industrial measurements. The instrument is similar to a military range finder except that the two telescopes forming the optical system of the range finder are replaced by two miscroscopes. In the instrument which has been constructed at the National Bureau of Standards, the magnification is approximately 85 and, under favorable conditions, the probable error of a single reading is approximately ±0.001 mm (±0.00004 inch). As the settings are made without mechanical contact the instrument is particularly well adapted for measurements where all danger of deformation of the object should be avoided. It can also be used for making a measurement which terminates at an optical image, and this possibility has been realized in a second optical coincidence gage which was built for the purpose of adjusting the sound reproducing mechanism of a motion-picture projector.

CONTENTS

Page
I. Introduction 229
II. The theory and use of an optical coincidence gage 230
III. Details of construction of the instrument built at the National Bureau of Standards 234
  1. Optical details 234
  2. Mechanical details 235
IV. Details of a second instrument which has been built 236

I. INTRODUCTION

The micrometer microscope is particularly adapted for the comparison or measurement of lengths which are limited by fiducial marks and which are parallel with the surface imaged by the microscope. Such an instrument is therefore well fitted for use in connection with line standards, and finds numerous applications on comparators, goniometers, and other measuring instruments. The comparison or measurement of end standards and the routine gaging of parts, such as is accomplished by the snap gage or micrometer caliper, requires the measurement of a length which lies normal to and is limited by a pair of surfaces. The requirement that such measurements be made by an optical method and without mechanical contact with the limiting surfaces presents a problem entirely different from that solved by the micrometer microscope.

The most obvious means for making such a measurement is the ordinary microscope, the position of the object plane on the axis being determined by the sharpness of the image. Unless objectives of large numerical aperture are employed, the lack of precision arising from the depth of focus is commonly a disadvantage and, if an objective of large numerical aperture is used, the working distance, for many purposes, becomes inconveniently small. The best results in using such focusing methods for measurements of this character, that is, measurements made normal to the surface imaged by the instrument, have probably been achieved by Arnulf, Van Heel, and Perrin.[1] The precision which they obtained leaves little to be desired, in fact, it is almost of the same order as that of the interferometer, but measurements can be made only to an optically regular, polished surface; a limitation not so serious, perhaps, in laboratory work, but probably an important obstacle to its introduction for industrial purposes. Interferometric methods constitute a second means for measuring lengths in the direction along which the light is traveling, but their great precision and sensitivity are accompanied by difficulties which have made it somewhat impracticable to apply such methods to measurements of intermediate accuracy.

In the instrument to be described a new means has been developed for making measurements in a direction normal to the surface observed, which permits measurements to be made with a precision intermediate between that of the usual screw micrometer and the interferometer. In this case, the operation is so simple that it may be used for routine industrial purposes whenever conditions make the use of an optical system necessary or advisable. There is no mechanical contact between the gage and the surface observed, and working distances as large as 50 mm can be consistently used with a probable error for a single setting not greater than ±0.001 mm.

The use of this instrument for industrial purposes offers advantages other than those of a favorable degree of precision. For measurements of high precision by mechanical methods the accuracy of a determination is always likely to be affected by deformation of the material at the point of contact even though the measurement is made to a surface of a most substantial object whereas, with the optical system to be described, the absence of mechanical contact permits measurements to be made on the most fragile of objects without the slightest danger or inaccuracy from deformation. The possibility of eliminating mechanical contact also enables one to make measurements of rotating parts in a lathe, of hot bodies without local cooling at point of contact, or of electrically charged bodies. A further advantage of an optical method is that measurements may be made to internal surfaces which are inaccessible to mechanical methods of measurement. For this purpose the instrument may be made in the form of a modified periscope, and may be so designed that the flexure of the parts forming the tube of the periscope does not affect the accuracy of measurement. Furthermore, one important industrial application of this instrument has been the measurement to an image formed by an optical system instead of to a material object, a measurement quite outside the range of a mechanical method.

II. THE THEORY AND USE OF AN OPTICAL COINCIDENCE GAGE

The basic principle of the optical coincidence gage will be understood by reference to Figure 1. Two microscopes are shown with their axes crossing at the axial object point. If each microscope is provided with a fixed cross hair it is evident that they may be so adjusted that an object placed at the intersection of the two axes will appear in coincidence with the cross hairs in each field. If now the object is displaced in a direction having a component parallel to the bisector of the axes of the microscopes its image must necessarily depart from the cross hair in one or both microscopes and a measure of this departure will be a measure of the displacement of the object. The instrument may be improved by borrowing an idea from the military, coincidence-type, self-contained base range finder. The fields of the two microscopes are accordingly brought together by a

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[1] Comptes Rendus, 188, pp. 860-861; 1929.

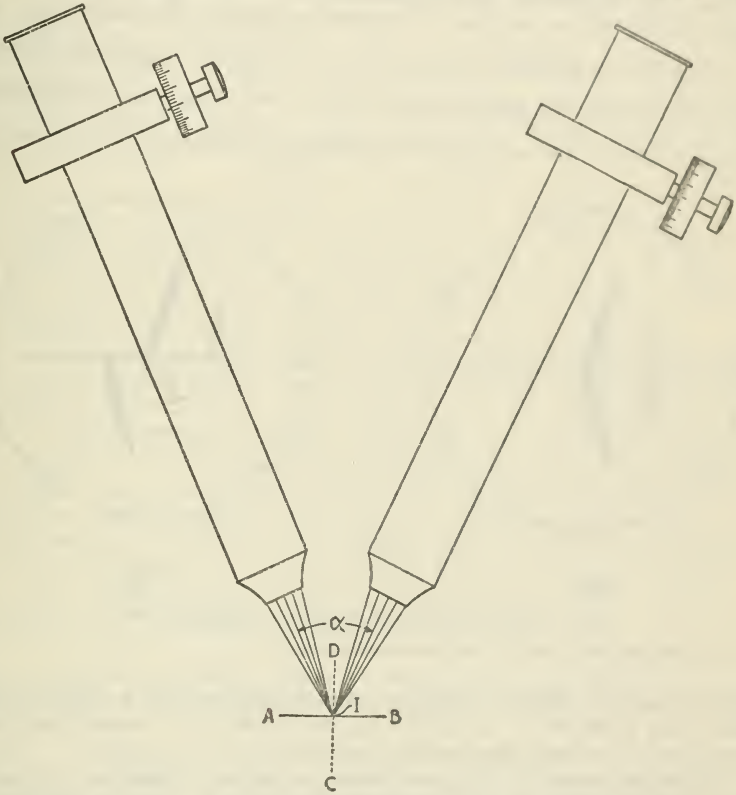

Figure 1.—*Diagrammatic sketch illustrating method of operation*

prism system so that both fields are seen at once through one ocular. With this prism half of each field is suppressed so that, on looking through the ocular one sees a circular field divided by a sharp diametrical dividing line, with the image on one side of the line formed by one objective, and that on the other side by the second.[2] The prisms connecting the two systems are so arranged that the two fields are perfectly symmetrical and consequently corresponding parts match on the two sides of the dividing line when the object is in the plane which makes equal angles with the two axes and contains their intersection. (The matching of the two fields can not be perfect at the edges because the object plane can not be normal to both optical axes at the same time, but with the relatively low magnification employed this introduces no appreciable difficulty, even at the edges of the field.) If now the object is displaced through a distance d, in any direction such as AB in a plane at right angles to the bisector CD of the angle between the two axes of the objective, then the image shifts bodily in both fields, without any disturbance of the symmetry, through the distance Md, where M is the magnification. If, however, the displacement is through a distance d along CD, the halves of the field move in opposite directions and fail to match by the distance $2Md\cancel{n} \sin \frac{\alpha}{2}$. The ratio of the sensitivities of the instrument to displacements in the two directions is therefore $2 \sin \frac{\alpha}{2}$, which, when α equals 25° (the value in the present instrument) reduces to 0.43; that is, the error of measurement for a displacement along the bisector of α will be approximately 2.5 times the corresponding error for a displacement normal to the bisector.

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[2] The ocular prism from a range finder of the "inverting type" can be used, in which case the same half of each field is suppressed. One field, however, is inverted thus making the two halves of the field symmetrical about the dividing line.

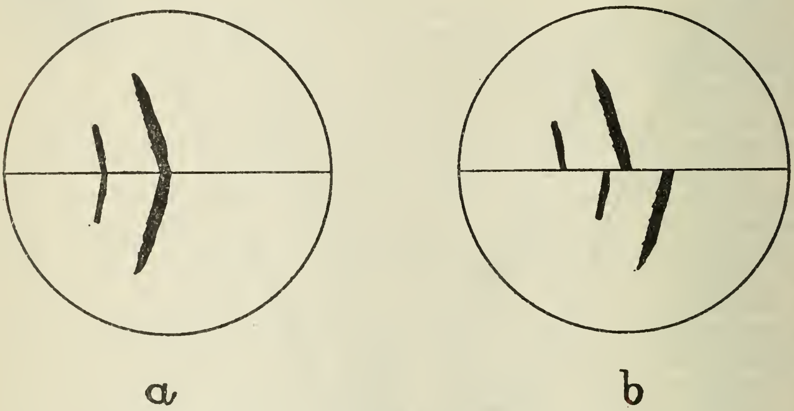

FIGURE 2.—*Field of view of optical coincidence gage*

a, Coincidence established; *b*, coincidence not established.

The appearance of the two fields, as viewed through the instrument will be made clear by reference to Figure 2. In the first sketch (*a*) the two fields match and the object has been brought into the position at which the reading is taken. In the second sketch (*b*) the adjustment has not been completed and the image is broken at the dividing line.

It is evident that the surface to which the measurement is to be made must possess "landmarks," such as tool marks, scratches or other markings on the surface, which can be readily identified. (This is not a severe restriction as few surfaces fail to show such marks when suitably magnified. By a simple modification,[3] however, the instrument may be adapted for measuring lengths terminated by optically regular reflecting surfaces which carry no surface markings.) Obviously, it is advantageous to so orient the surface that the images of these markings lie with their longer dimensions approximately normal to the dividing line in the field of the instrument as illustrated in Figure 2.

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[3] To measure to an optically regular reflecting surface an illuminated slit or other brightly illuminated target is mounted on the optical coincidence gage. The setting is made on the image of the target formed by reflection at the optical surface. If the two surfaces between which the measurement is to be made are plane or have the same curvature no correction need be applied for the use of the reflected image. If the two surfaces have different curvatures an easily evaluated constant must be applied to the result obtained.

From the above discussion it is evident that there exists a reference plane, having a fixed relation to the instrument, into which, a surface must be brought if the two halves of the field are to match. When the surface departs from this reference plane the fields fail to match, and it has been found that this failure provides a convenient means for measuring a departure as small as ±0.001 mm. It follows that the optical system, as described, functions as a sensitive indicator, for determining the position of a surface or its departure from a standard position, but it differs from other indicators in that no mechanical contact with, or particular quality of, the given surface is required. "Optical contact" is substituted for mechanical contact and diffuse rather than specular reflection can be used. Moreover, these advantages are combined with high sensitivity in an instrument adapted for industrial applications. This optical system has been devised for use as part of an instrument which is being developed for gaging internal threads and which will be described in a later paper.

A dimension to be gaged by the optical coincidence gage must possess the characteristics of an end standard rather than of a line standard; that is the dimension must be terminated by two surfaces which are normal to the dimension or which have two tangent planes normal to it. The micrometer caliper, snap gage, and similar devices deal with lengths of this character, and the measurement of such lengths constitute a large portion of the gaging operations in industrial establishments. For one method of using the optical coincidence gage for a measurement of this nature a suitable mounting must be provided having an anvil which can be translated through a measured distance. The anvil is first brought into the reference plane and coincidence established. The object to be gaged is next placed with one of the fiducial surfaces in contact with the anvil which is then translated until the second fiducial surface is brought into the reference plane and the distance through which the anvil was translated is the required measurement.

With this method of measurement there is mechanical contact between the anvil and the lower fiducial surface. However, there is no mechanical contact at the upper surface and the object is under no stresses other than those introduced by its own weight. For those cases in which entire freedom from mechanical contact is required two complete optical systems, one directed at each surface, may be employed.

In another method of application of the gage the test surfaces remain fixed and the translation of a prism of small angle along the axis of one of the microscope systems shifts, with respect to the instrument, the location of the reference plane for which coincidence is obtained. The scale for measuring this prism translation may be graduated to read directly the amount of this reference-plane shift and a very open scale may be secured by a suitable choice of refracting angle for the prism. This method, however, can not be applied to the measurement of lengths greater than the distance through which the object can be displaced without the necessity of changing the focus. This is the method of measurement used on the instrument described in Section IV.

III. DETAILS OF CONSTRUCTION OF THE INSTRUMENT BUILT AT THE NATIONAL BUREAU OF STANDARDS

1. OPTICAL DETAILS

The arrangement of the optical parts in the initial instrument which has been constructed by the National Bureau of Standards is illustrated by Figure 3. The locations of the two objectives and the paths of the light rays through the several reflecting prisms to the common ocular are clearly indicated. The ocular prism is of the standard type used in a 1 m base military range finder. This prism was selected because of its availability although a prism of simpler and less expensive construction would have served quite as well for the present purpose. In order to obtain satisfactory results it is necessary that the two halves of the optical system be so adjusted that the two exit pupils are in coincidence. If this adjustment is not secured the relative brightness of the two halves of the field will vary in a disturbing manner as the position of the eye is changed. The mechanism for fine adjustment of the reflecting prisms (which is described in Section III, 2) was very useful in securing this coincidence of the exit pupils.

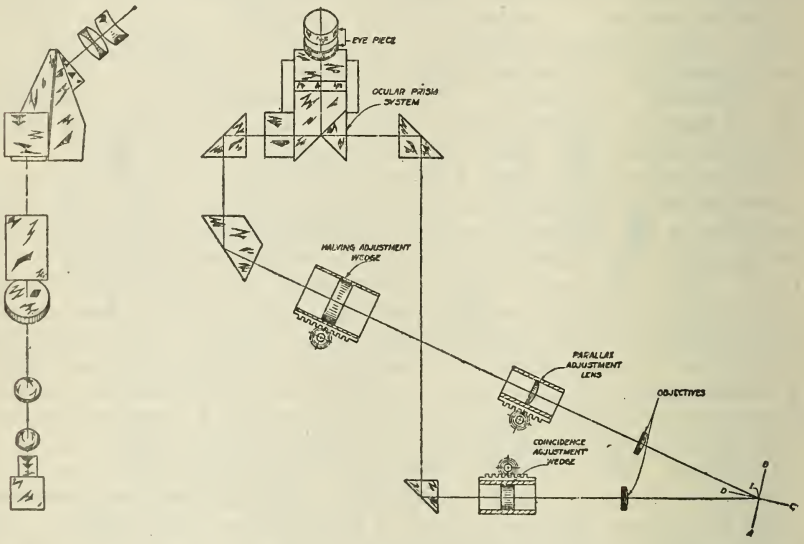

FIGURE 3.—*Optical system of coincidence gage*

To measure with precision it is necessary that the images in the two halves of the field be magnified to the same scale, that one field show no parallax with respect to the other, that the two fields match when in the position of best focus, and that the dividing line cut the image of a line lying transverse to it at exactly the same point in the two fields. These conditions are easily maintained when they are once established, but suitable fine adjustment mechanism must be provided for such purposes. To make the two images the same size one objective is shifted in its tube to bring it farther from or closer to the object. After this has been done, the two images, in general, will not lie in the same plane and there will be parallax. To remove this the "parallax adjustment lens," a weak supplementary lens located back of one of the objectives, is displaced along the axis. If the required correction for parallax is large it may be necessary to readjust the objective and make a second adjustment for parallax in order to secure both equality of magnification and freedom from parallax. The "parallax adjustment lens" is given its correct position by a rack and pinion movement operated by a key which fits over the end of the pinion shaft. When this key is removed all parts are flush and there is but slight danger of an accidental displacement. After equal magnification and freedom from parallax have been secured the object is brought into the plane of best focus by displacing the instrument or the object. In general, the two fields will not match nor will they be symmetrically placed with reference to the dividing line. To remedy these defects the "halving adjustment wedge" and the "coincidence adjustment wedge" are provided and they also are movable along the axis by means of the key and suitable rack and pinion movement. The first mentioned wedge has its refracting edge parallel to the plane of the drawing and when it is moved it shifts one image in a direction at right angles to the dividing line, thus enabling a symmetrical appearance of the two fields to be obtained. This is analogous to the "halving adjustment" of the range finder. The "coincidence adjustment wedge" has its refracting edge normal to the plane of the drawing, and by its movement one field is caused to shift relative to the other in a direction parallel to the dividing line thus enabling the two fields to be brought to a match when the object is in the position for best focus. This adjustment is analogous to the "infinity adjustment" of the range finder.

For this instrument the magnification is approximately 85 diameters, the angle between the axes of the two objectives is 25°, and the working distance, measured from the front surface of the objective to the object surface is 50 mm. The precision of setting depends, as is to be expected, upon the character of the target. With a fine opaque wire, against a bright field, it is not difficult to obtain settings for which the probable error of a single determination is ±0.001 mm.

2. MECHANICAL DETAILS

Figure 4 is a reproduction of the completed coincidence optical gage as constructed at the National Bureau of Standards. The body of the instrument is composed of two aluminum castings, one forming the support, the other the cover for the optical parts. The peculiar form given to the system, with the two objectives carried in the nose piece projecting to the right, was adopted because of the special purposes for which the instrument was designed.[4] The "parallax adjustment lens" and the "coincidence adjustment wedge" indicated in Figure 3, are located in the nose piece and do not show in Figure 4.

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[4] This instrument has been developed to form the optical part of a device for measuring internal threads. The extension to the nose piece shown in Figures 4 and 5 and not indicated in Figure 3 is an attachment added for this same purpose.

These parts are adjusted by a key which enters the instrument from the back. The other prisms are clearly visible and may be readily identified by reference to Figure 3. Each of the four reflecting prisms is mounted on a small turntable held snugly in its seat by a nut and a spring washer on the back of the instrument. For each turntable two screws enter the edge of the base of the instrument and bear against two faces cut on the turntable in such a manner that when the two screws are alternately tightened they tend to rotate the turntable in opposite directions. These screws provide a means for orienting the prisms precisely. After such an adjustment has been made the heads of the adjusting screws are covered with a strip of metal which is secured in place to prevent the accidental disturbance of the adjustment. This construction is clearly shown in Figure 5.

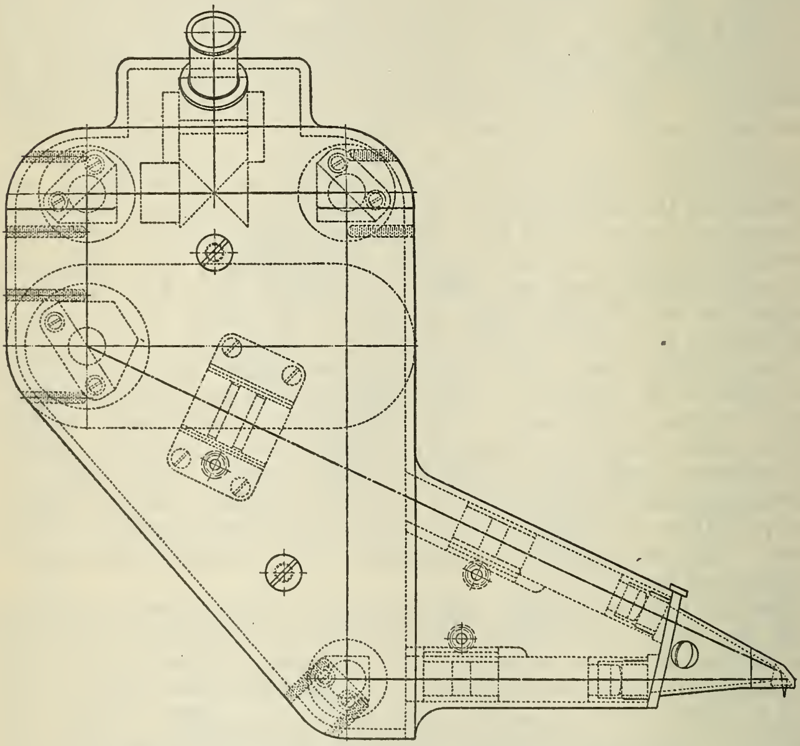

FIGURE 5.—*Mechanical details of optical coincidence gage*

IV. DETAILS OF A SECOND INSTRUMENT WHICH HAS BEEN BUILT

A problem encountered by the Baush & Lomb Optical Co. was solved at the bureau's suggestion by the adoption of the optical system of the coincidence optical gage. Figure 6 is an illustration of the instrument which they have built for use in the assembly and adjustment of a portion of the sound-reproducing device on a motion-

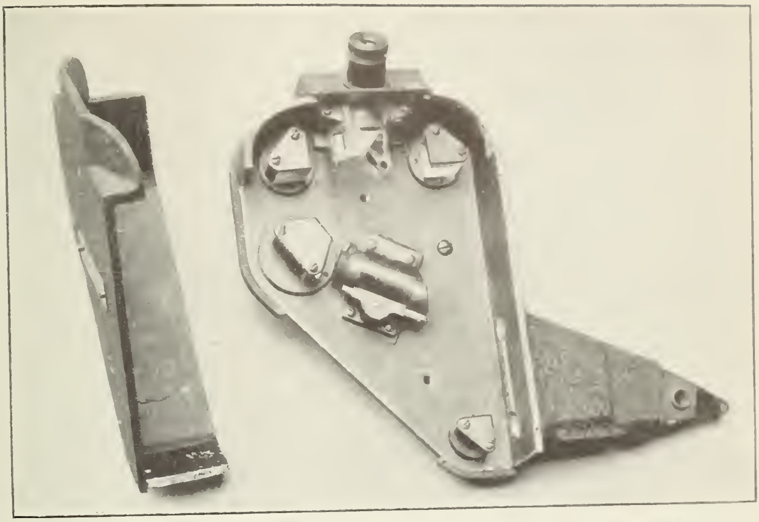

FIGURE 4.—*View of complete instrument with the cover removed*

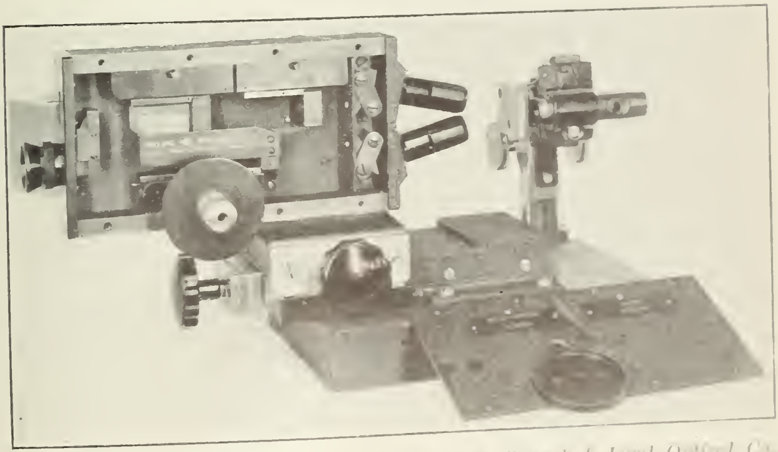

FIGURE 6.—*Optical coincidence gage built by the Bausch & Lomb Optical Co. for the adjustment of sound reproducing motion-picture apparatus*

picture projector. A small image of a slit is produced by a well-corrected condensing system of large angular aperture, and this image is to be adjusted to fall very precisely in the plane of the film. Obviously, an optical method must be used to fix the position of the slit image. The image may be observed by a microscope focussed on the plane to which the slit is to be adjusted, but if the magnification employed is sufficient to give the desired precision, the aberration of the image is made so evident that considerable skill and judgment must be acquired before a satisfactory adjustment can be made. It happens that the angular aperture of the cone of rays forming the image is large and permits the image to be observed simultaneously through two microscope systems, such as those of the coincidence gage. It seemed, therefore, that his type of instrument would serve as an excellent indicator for fixing the position of the slit. A trial with the instrument built at the National Bureau of Standards demonstrated that the gage could be applied satisfactorily and the Baush & Lomb Optical Co. accordingly built the instrument illustrated in Figure 6. Small displacements of the slit are measured by a measuring wedge or prism, which, by its displacement along the optical axis, shifts the axis of one-half of the optical system slightly, and thus displaces the point of intersection of the two axes. This is substantially the same measuring device that is employed in one type of range finder. The scale parallel to which the measuring wedge moves is clearly shown in Figure 6, and is graduated to read directly in terms of the displacement of the object. The numbers for the scale, as can be seen from the illustration, are reversed in order that they may read correctly after a single reflection in a mirror, which enables the scale to be conveniently read by the observer when in a position to look through the eyepiece. The support for this mirror can be seen on the cover of the instrument. The use of a measuring wedge with a small refracting angle enables a very open scale to be secured. The entire scale shown in the illustration corresponds to a motion of the object of only 0.006 inch and the probable error for a single setting is of the order of ± 0.00002 inch.

WASHINGTON, October 1, 1930.

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